Soil & Tillage Research 190 (2019) 22–30

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Meta-analysis on carbon sequestration through Conservation Agriculture in Africa

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ARTICLE INFO

Keywords:
Carbon sequestration
No-tillage
Groundcovers
Climate change

ABSTRACT

Africa is the smallest contributor to global greenhouse gas emissions among the continents, but the most vulnerable to the impacts of climate change. The effects will not be limited to a rising average temperature and changing rainfall patterns, but also to increasing severity and frequency in droughts, heat stress and floods.

Agriculture is not only impacted upon by climate change but also contributes to global warming. However, not all agricultural systems affect negatively climate change. Conservation Agriculture (CA) is a farming system that promotes continuous no or minimum soil disturbance (i.e. no tillage), maintenance of a permanent soil mulch cover, and diversification of plant species. Through these principles it enhances biodiversity and natural biological processes above and below the ground surface, so contributing to increased water and nutrient use efficiency and productivity, to more resilient cropping systems, and to improved and sustained crop production. Conservation Agriculture is based on the practical application of three interlinked principles along with complementary good agricultural practice. The characteristics of CA make it one of the systems best able to contribute to climate change mitigation by reducing atmospheric greenhouse gas concentration.

In this article, the carbon sequestration potential of CA is assessed, both in annual and perennial crops, in the different agro-climatic regions of Africa. In total, the potential estimate of annual carbon sequestration in African agricultural soils through CA amounts to 143 Tg of C per year, that is 524 Tg of CO_2 per year. This figure represents about 93 times the current sequestration figure.

1. Introduction

Africa is the smallest contributor to global greenhouse gas emissions (GHGs) among the continents, but the most vulnerable to the impacts of climate change (UNFCCC, 2016). According to the Intergovernmental Panel on Climate Change (IPCC), temperatures across Africa are expected to increase by 2–6 °C within the next 100 years (IPCC, 2014). The effects will not be limited to a rising average temperature and changing rainfall patterns, but also to increasing severity and frequency in droughts, heat stress and floods (Niang et al., 2014; Hummel, 2015; Rose, 2015). These climatic risks have a direct negative impact on the natural resources supporting agricultural production processes with a detrimental impact on food security and livelihoods (Awojobi and Tetteh, 2017; Abebe, 2014; Science for Environmental Policy, 2015). The agricultural sector in Africa has been impacted by flooding, droughts, soil erosion, land degradation and deforestation, leading to human migration within Africa and to out migration from Africa.

Agriculture is not only impacted upon by climate change but also contributes to global warming. Even if agriculture would not be the only productive sector affected by global warming, the impacts on it would definitely have negative effects on food security and social welfare. Crops need adequate land, water, sunlight and temperature to grow and complete their production cycles. Global warming has already altered the duration of the growing season in some areas. The periods of

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https://doi.org/10.1016/j.still.2019.02.020
Received 9 December 2018; Received in revised form 18 February 2019; Accepted 20 February 2019
Available online 01 March 2019

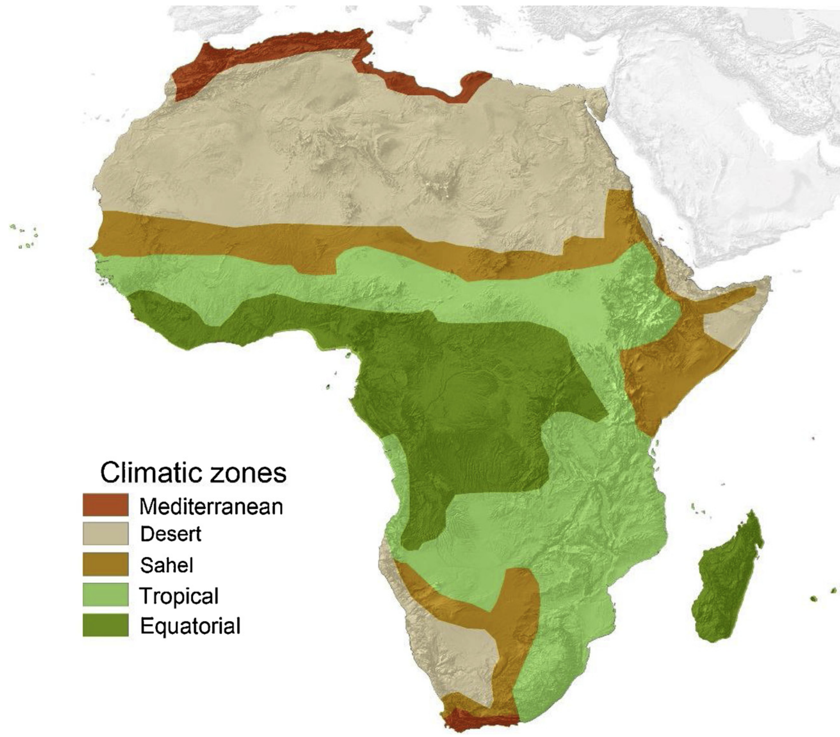

Fig. 1. Climatic zones of Africa. Source: Authors' diagram based on Ngaira (2007) and www.gifex.com.

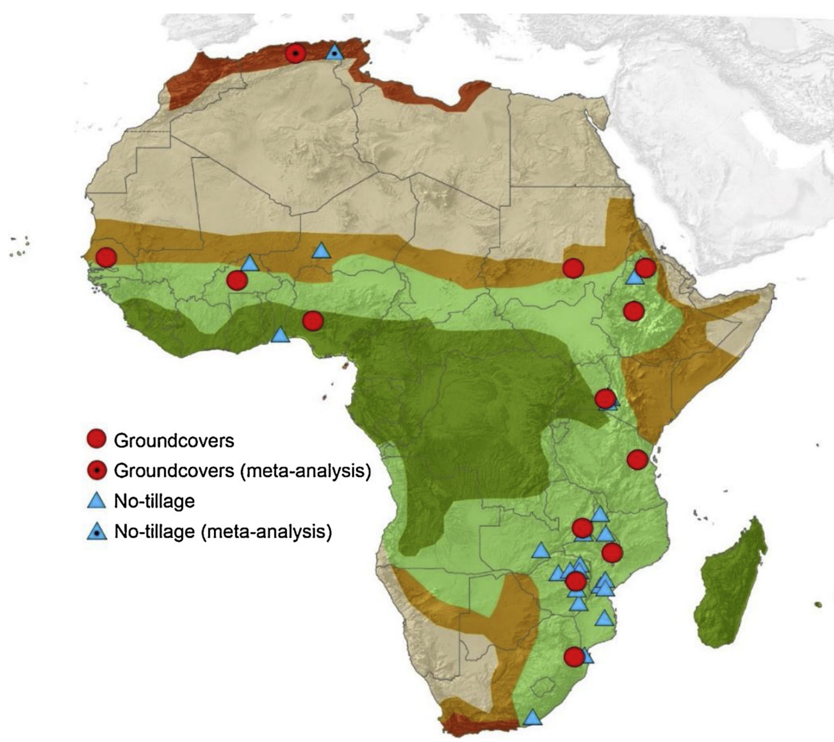

Fig. 2. Geographical distribution of studies addressing carbon sequestration per climatic zone.

flowering and harvest of cereals are already several days ahead. It is foreseeable that these changes may continue to occur in many regions (EEA, 2016). The sector needs to adapt to the changes in climatic conditions and also help in mitigation. Agriculture, which is part of the AFOLU sector (Agriculture, Forestry, and Other Land Use) is unique, since its climate change mitigation potential is derived from both an enhancement of removals of GHGs from the atmosphere, and a reduction of emissions through management of land, crops and livestock (Smith et al., 2014).

Africa remains a food deficit region, yet it has potential to become a future 'bread basket', and the sustainable intensification of agricultural output, with a focus on soil and water conservation and optimum use of production inputs with minimum negative impact on the environment is part of the solution (Conway, 2012). Lal (2008) alerts of the effects of projected climate change on yield of food crops in Africa that may reach significant declines of 17.2% in wheat, 14.6% in sorghum and 13.1% in

Table 1
Carbon sequestration rates in Conservation Agriculture (CA) for each climatic zone.
Source: Carbon sequestration rates based on the papers reviewed and listed in the references.

	Carbon sequestration rate for CA in annual crops (Mg ha^{-1} yr^{-1})	Carbon sequestration rate for CA in woody crops (Mg ha^{-1} yr^{-1})
Mediterranean	0.44	1.29
Sahel	0.50	0.12
Tropical	1.02	0.79
Equatorial	1.56	0.26

Table 2
Current soil organic carbon (SOC) fixed annually by CA cropland systems compared to systems based on tillage agriculture in Africa.
*Source: Kassam et al., 2018.

Country	No-tillage adoption* (ha)	Carbon sequestration rate in no-tillage (Mg ha^{-1} yr^{-1})	Current annual carbon sequestration (Mg yr^{-1})	Climatic zone
Algeria	5,600	0.44	2,464	Mediterranean
Ghana	30,000	1.56	46,800	Equatorial
Kenya	33,100	1.02	33,762	Tropical
Lesotho	2,000	1.02	2,040	Tropical
Madagascar	9,000	1.56	14,040	Equatorial
Malawi	211,000	1.02	215,220	Tropical
Morocco	10,500	0.44	4,620	Mediterranean
Mozambique	289,000	1.02	294,780	Tropical
Namibia	340	0.50	170	Sahel
South Africa	439,000	1.02	447,780	Tropical
Sudan	10,000	0.50	5,000	Sahel
Swaziland	1,300	1.02	1,326	Tropical
Tanzania	32,600	1.02	33,252	Tropical
Tunisia	12,000	0.44	5,280	Mediterranean
Uganda	7,800	1.56	12,168	Equatorial
Zambia	316,000	1.02	322,320	Tropical
Zimbabwe	100,000	1.02	102,000	Tropical
TOTAL	**1,509,240**		**1,543,022**	

maize. For many developing countries, the main concern regarding agriculture relates to food security, poverty alleviation, economic development and adaptation to the potential impacts of climate change.

A well designed and executed soil management system has the potential to increase yields (e.g., in sub-Saharan Africa) while also providing a range of co-benefits such as increased soil organic matter (Keating et al., 2013; Kassam et al., 2017a). Two-thirds of developing countries have implemented strategic plans to mitigate greenhouse gas (GHG) emissions from agriculture (Wilkes et al., 2013).

In this context, Conservation Agriculture (CA) is a sustainable agriculture system, able to produce food and other agricultural products in all land-based agroecologies (Kassam et al., 2018). According to the Food and Agriculture Organization of the United Nations (FAO, 2018a), CA is a farming system that promotes continuous no or minimum soil disturbance (i.e. no tillage), maintenance of a permanent soil mulch cover, and diversification of plant species. It enhances biodiversity and natural biological processes above and below the ground surface, so contributing to increased water and nutrient use efficiency and productivity, to more resilient cropping systems, and to improved and sustained crop production. CA is based on the practical application of three interlinked principles along with complementary good agricultural practice, namely:

(1) Avoiding or minimizing mechanical soil disturbance involving seeding or planting directly into untilled soil, eliminating tillage altogether once the soil has been brought to good condition, and keeping soil disturbance from cultural operations to the minimum possible.
(2) Maintaining year-round biomass mulch cover over the soil, including specially introduced cover crops and intercrops and/or the mulch provided by retained biomass and stubble from the previous crop.
(3) Diversifying crop rotations, sequences and associations, adapted to local environmental and socio-economic conditions, and including appropriate nitrogen fixing legumes; such rotations and associations contribute to maintaining biodiversity above and, in the soil, add biologically fixed nitrogen to the soil-plant system, and help avoid build-up of pest populations. In CA, the sequences and rotations of crops encourage agrobiodiversity as each crop will attract different overlapping spectra of microorganisms and natural enemies of pests.

No-tillage is clearly identified as a CA technique, whereas the application of Conservation Agriculture in perennial crops has been less studied. The agronomical practise of CA in woody crops are the groundcovers, whereby the soil surface between rows of trees remains protected against erosion by a cover. With this technique, at least 30% of the soil is protected either by sown cover crops, spontaneous vegetation or inert covers, such as pruning residues or tree leaves. For the establishment of sown cover crops and the spread of inert covers, farmers must use methods in coherence with CA principle of minimum soil disturbance (Gonzalez-Sanchez et al., 2015).

In both type of crops, annual or perennial, the characteristics of CA make it one of the systems best able to contribute to climate change mitigation by reducing atmospheric GHGs concentration. On the one hand, the changes introduced by CA in the carbon dynamics in the soil lead directly to an increase in soil C (Reicosky, 1995; Lal, 2008). This effect is known as 'soil's carbon sink'. At the same time, the drastic reduction in the amount of tillage and the mechanical non-alteration of the soil reduce CO_2 emissions arising from energy saving and the reduction in the rates of the mineralization of soil organic matter (Carbonell-Bojollo et al., 2011; Kassam et al., 2017a). CA adoption requires a much lower level of capital investment and production inputs and is thus more readily applicable to smallholder farmers in low income countries (Kassam et al., 2017b).

Soil carbon sequestration is a process in which CO_2 is removed from the atmosphere and stored in the soil carbon pool. This process is primarily mediated by plants through photosynthesis, with carbon stored in the form of soil organic carbon (SOC) (Lal, 2008). In terms of climate change mitigation, CA contributes the increase of SOC, whilst reducing the emissions of carbon dioxide. On the one hand, the decomposition of the crop biomass on the soil surface increase soil organic matter and soil organic carbon. On the other hand, emissions are reduced as a result of less soil carbon combustion due to no-tillage, and less fuel burning because of fewer field operations and lower energy use for seeding and crop establishment. The net sum effect of these processes results in an increase in the carbon sink effect in the soil, leading to a net increase of soil organic carbon; measured in Mg of carbon in soil per hectare per year (Mg ha^{-1} yr^{-1}). Numerous scientific studies confirm that soils are an important pool of active carbon (González-Sánchez et al., 2012), and play a major role in the global carbon cycle.

Several international initiatives have identified CA as a major contributor to the mitigation and adaptability of agricultural land use to climate change. The initiative "4 per 1000" (4p1000, 2015), launched by France on 1 December 2015 at the COP 21 in Paris, aims to demonstrate that agriculture, and in particular agricultural soils, can play a crucial role where food security and climate change are concerned. The following year, the Adaptation of African Agriculture (AAA, 2016) was identified as one of the priorities of the Moroccan presidency for COP22 in Marrakesh. The Triple A aims to reduce the vulnerability of Africa and its agriculture to climate change. Both 4p1000 and AAA are governmentally supported, and show that agriculture can provide some practical solutions to the challenge and threats posed by climate

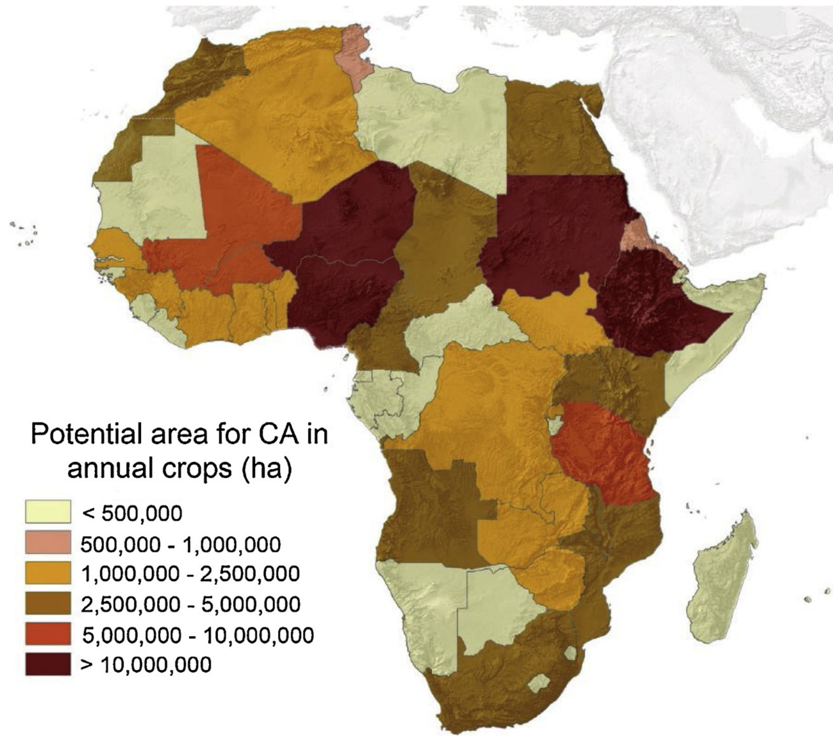

Fig. 3. Potential area for the application of CA in annual crops in Africa in 2016. Source: Authors diagram based on FAOSTAT, 2018.

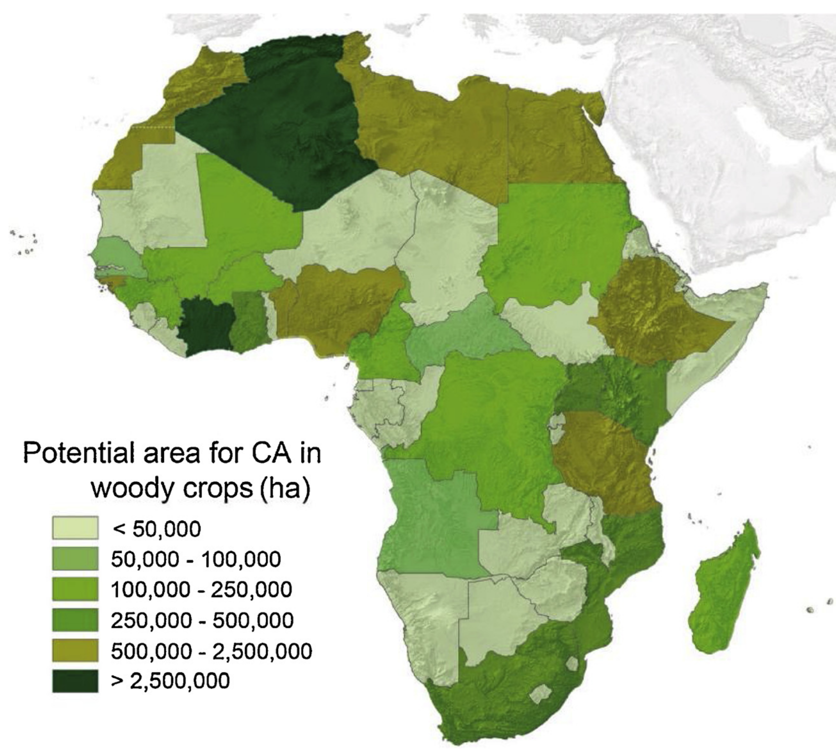

Fig. 4. Potential area for the application of CA in woody crops in Africa in 2016. Source: Authors diagram based on FAOSTAT (2018).

change. The promotion of CA is among the key solutions and recommendations identified in both initiatives. The "4 per 1000" initiative intends to increase soil organic matter and carbon sequestration through the implementation of agricultural systems and practices adapted to local environmental, social and economic conditions, whereas the AAA promotes and supports three over-arching solution clusters to enhance soil management through soil fertility and crop fertilisation; arboriculture and agroforestry; and agroecological innovations and carbon sequestration. CA has also been incorporated into the regional agricultural policies, and increasingly, has been 'officially' recognized as a core element of climate-smart agriculture (FAO, 2016, 2017; Kassam et al., 2017b).

At present some 11 percent (1.5 Gha) of the globe's land surface (13.4 Gha) is used in crop production (arable land and land under

Table 3
Potential annual carbon sequestration in annual crops due to no-tillage. Potential adoption of no-tillage elaborated on country statistics of eligible crops based on FAOSTAT (FAO, 2018b).

Country	Potential adoption of no-tillage (ha)	Carbon sequestration rate in no-tillage (Mg ha^{-1} yr^{-1})	Potential annual carbon sequestration in no-tillage (Mg yr^{-1})	Climatic zone
Algeria	2,298,018	0.44	1,011,128	Mediterranean
Angola	1,294,527	1.56	2,019,462	Equatorial
Angola	1,294,527	1.02	1,320,418	Tropical
Benin	1,763,758	1.56	2,751,462	Equatorial
Botswana	120,460	0.50	60,230	Sahel
Burkina Faso	6,290,742	1.02	6,416,557	Tropical
Burundi	446,863	1.02	455,800	Tropical
Cabo Verde	63,396	1.02	64,664	Tropical
Cameroon	1,630,294	1.56	2,543,258	Equatorial
Cameroon	1,630,294	1.02	1,662,899	Tropical
Central African Republic	330,367	1.56	515,373	Equatorial
Chad	2,052,614	0.50	1,026,307	Sahel
Chad	2,052,614	1.02	2,093,666	Tropical
Comoros	22,362	1.02	22,809	Tropical
Congo	49,484	1.56	77,195	Equatorial
Côte d'Ivoire	1,046,568	1.56	1,632,646	Equatorial
Democratic Republic of the Congo	2,435,696	1.56	3,799,686	Equatorial
Eritrea	598,467	0.50	299,234	Sahel
Ethiopia	3,032,626	0.50	1,516,313	Sahel
Ethiopia	9,097,877	1.02	9,279,835	Tropical
Gabon	40,598	1.56	63,333	Equatorial
Gambia	213,313	1.02	217,579	Tropical
Ghana	1,879,696	1.56	2,932,326	Equatorial
Guinea	676,016	1.56	1,054,585	Equatorial
Guinea	676,016	1.02	689,536	Tropical
Guinea-Bissau	57,660	1.02	58,813	Tropical
Kenya	2,300,622	0.50	1,150,311	Sahel
Kenya	2,300,622	1.02	2,346,634	Tropical
Lesotho	89,068	1.02	90,849	Tropical
Liberia	8,532	1.56	13,310	Equatorial
Libya	326,268	0.44	143,558	Mediterranean
Madagascar	361,970	1.56	564,673	Equatorial
Malawi	2,864,440	1.02	2,921,729	Tropical
Mali	2,876,307	0.50	1,438,154	Sahel
Mali	2,876,307	1.02	2,933,833	Tropical
Mauritania	342,236	0.50	171,118	Sahel
Mauritius	395	1.56	616	Equatorial
Morocco	4,164,886	0.44	1,832,550	Mediterranean
Mozambique	3,004,979	1.02	3,065,079	Tropical
Namibia	303,653	0.50	151,827	Sahel
Niger	16,362,647	0.50	8,181,324	Sahel
Nigeria	10,557,289	1.56	16,469,370	Equatorial
Nigeria	10,557,289	1.02	10,768,434	Tropical
Reunion	5,066	1.56	7,903	Equatorial
Rwanda	519,023	1.56	809,676	Equatorial
Rwanda	519,023	1.02	529,403	Tropical
Sao Tome and Principe	949	1.56	1,480	Equatorial
Senegal	724,221	0.50	362,111	Sahel
Senegal	724,221	1.02	738,705	Tropical
Sierra Leone	253,887	1.56	396,064	Equatorial
Somalia	435,096	0.50	217,548	Sahel
South Africa	587,257	0.44	258,393	Mediterranean
South Africa	587,257	0.50	293,629	Sahel
South Africa	1,761,771	1.02	1,797,006	Tropical
South Sudan	1,230,241	1.02	1,254,846	Tropical
Sudan	15,262,789	0.50	7,631,395	Sahel
Swaziland	86,070	1.02	87,791	Tropical
Tanzania	9,693,740	1.02	9,887,615	Tropical
Togo	1,524,877	1.56	2,378,808	Equatorial
Tunisia	997,413	0.44	438,862	Mediterranean
Uganda	1,523,709	1.56	2,376,985	Equatorial
Uganda	1,523,709	1.02	1,554,183	Tropical
Zambia	1,648,278	1.02	1,681,244	Tropical
Zimbabwe	2,171,103	1.02	2,214,525	Tropical
TOTAL	**142,172,059**		**130,746,653**	

permanent crops) (FAO, 2003), therefore a major shift from tillage-based agriculture to climate smart systems, such as CA, would have a significant impact on global climate, food security and society. The aim of this study is to provide knowledge with a solid scientific base on the carbon sequestration potential of CA, both in annual and perennial crops, in the different agro-climatic regions of Africa.

2. Material and methods

The results presented in this paper are based on a literature review of scientific articles published in peer reviewed journals. The terms "Conservation Agriculture; carbon sequestration; Africa; climate change mitigation; no-tillage; groundcovers" have been consulted at the scientific databases *sciencedirect.com* and *webofknowledge.com*.

This review has been carried out for the different climatic zones of Africa (Fig. 1) using as baseline reported carbon sequestration rates under CA and the current area of CA adoption in annual and perennial cropping systems. It then estimated the potential of carbon sequestration based on both the potential sequestration rates in annual and perennial cropping systems and different climatic zones, and the potential area that could be converted from conventional tillage agriculture to CA across Africa. Fig. 2 shows the geographical distribution of the studies. No data for carbon sequestration in desert areas is presented, as no articles with a carbon sequestration rate of CA have been found, and there is little expectation of a significant carbon increase in those environments as a result of farming activities.

The methodology for obtaining the carbon sequestration rates is described in González-Sánchez et al. (2012). To estimate the potential of CA for C sequestration, in each study, the increase of observed organic matter in the conservation system was evaluated in relation to conventional tillage. C increases are proposed in terms of quantities of C from the organic carbon (OC) in the soil. To estimate the potential area suitable for the adoption of CA the areas of different crops in the different climatic zones as provided by FAOSTAT (FAO, 2018b) was used. Among the annual crops, those best adapted to no-tillage CA systems were selected as eligible crops: cereals, pulses, oilseeds, cotton, among other crops that do not need soil disturbance for harvesting, whereas most of the woody perennial crop areas were found suitable for CA. It could not be identified if root crops are in rotation with eligible crops.

In climate change international agreements, emissions are referred to carbon dioxide; however, soil carbon studies refer to carbon. For transforming carbon into carbon dioxide, the coefficient of 3.67 was used. The atomic weight of carbon is 12 atomic mass units, while the weight of carbon dioxide is 44, because it also includes two oxygen atoms that each weigh 16. So, to switch from one to the other, one Mg of carbon equals 44/12 = 3.67 Mg of carbon dioxide.

3. Results and discussion

According to the latest statistics available, farmers in almost 20 African countries are practising CA, including Algeria, Ghana, Kenya, Lesotho, Madagascar, Malawi, Morocco, Mozambique, Namibia, South Africa, Sudan, Swaziland, Tanzania, Tunisia, Uganda, Zambia and Zimbabwe (Kassam et al., 2018).

The most recent figures of adoption of CA for annual crops in Africa

Table 4
Potential annual carbon sequestration in woody crops due to groundcovers. Potential adoption of groundcovers elaborated on country statistics of eligible crops based on FAOSTAT (FAO, 2018b).

Country	Potential adoption of groundcovers (ha)	Carbon sequestration rate in groundcovers (Mg ha^{-1} yr^{-1})	Potential annual carbon sequestration in groundcovers (Mg yr^{-1})	Climatic zone
Algeria	813,371	1.29	1,049,249	Mediterranean
Angola	39,795	0.26	10,347	Equatorial
Angola	39,795	0.79	31,438	Tropical
Benin	785,872	0.26	204,327	Equatorial
Botswana	32	0.12	4	Sahel
Burkina Faso	167,148	0.79	132,047	Tropical
Burundi	15,981	0.79	12,625	Tropical
Cabo Verde	443	0.79	350	Tropical
Cameroon	60,607	0.26	15,758	Equatorial
Cameroon	60,607	0.79	47,879	Tropical
Central African Republic	55,932	0.26	14,542	Equatorial
Chad	4,316	0.12	518	Sahel
Chad	4,316	0.79	3,409	Tropical
Comoros	989	0.79	781	Tropical
Congo	18,790	0.26	4,885	Equatorial
Côte d'Ivoire	4,312,885	0.26	1,121,350	Equatorial
Democratic Republic of the Congo	113,234	0.26	29,441	Equatorial
Equatorial Guinea	11,587	0.26	3,013	Equatorial
Ethiopia	201,770	0.12	24,212	Sahel
Ethiopia	605,309	0.79	478,194	Tropical
Gabon	520	0.26	135	Equatorial
Gambia	3,841	0.79	3,034	Tropical
Ghana	329,980	0.26	85,795	Equatorial
Guinea	94,616	0.26	24,600	Equatorial
Guinea	94,616	0.79	74,746	Tropical
Guinea-Bissau	558,346	0.79	441,093	Tropical
Kenya	133,040	0.12	15,965	Sahel
Kenya	133,040	0.79	105,102	Tropical
Liberia	7,294	0.26	1,896	Equatorial
Libya	509,133	1.29	656,782	Mediterranean
Madagascar	227,889	0.26	59,251	Equatorial
Malawi	16,138	0.79	12,749	Tropical
Mali	96,010	0.12	11,521	Sahel
Mali	96,010	0.79	75,848	Tropical
Mauritius	203	0.26	53	Equatorial
Morocco	1,686,040	1.29	2,174,992	Mediterranean
Mozambique	260,859	0.79	206,079	Tropical
Namibia	7,061	0.12	847	Sahel
Niger	40,600	0.12	4,872	Sahel
Nigeria	888,532	0.26	231,018	Equatorial
Nigeria	888,532	0.79	701,940	Tropical
Reunion	690	0.26	179	Equatorial
Rwanda	24,318	0.26	6,323	Equatorial
Rwanda	24,318	0.79	19,211	Tropical
Sao Tome and Principe	429	0.26	112	Equatorial
Senegal	32,019	0.12	3,842	Sahel
Senegal	32,019	0.79	25,295	Tropical
Seychelles	81	0.79	64	Tropical
Sierra Leone	36,034	0.26	9,369	Equatorial
Somalia	4,299	0.12	516	Sahel
South Africa	46,198	1.29	59,595	Mediterranean
South Africa	46,198	0.12	5,544	Sahel
South Africa	138,593	0.79	109,488	Tropical
South Sudan	1,943	0.79	1,535	Tropical
Sudan	117,096	0.12	14,052	Sahel
Swaziland	13,746	0.79	10,859	Tropical
Tanzania	1,263,844	0.79	998,437	Tropical
Togo	48,816	0.26	12,692	Equatorial
Tunisia	2,196,810	1.29	2,833,885	Mediterranean
Uganda	191,748	0.26	49,854	Equatorial
Uganda	191,748	0.79	151,481	Tropical
Zambia	8,534	0.79	6,742	Tropical
Zimbabwe	27,886	0.79	22,030	Tropical
TOTAL	**17,832,438**		**12,413,790**	

(season 2015/16) totaled 1.5 Mha. This corresponds to some 211% increase from 0.48 Mha in 2008/09 (Kassam et al., 2018). This significant increase is because of the many years of research showing positive results for CA systems, plus increasing attention being paid to CA systems by governments, NEPAD (New Partnership for Africa's Development), and NGOs such as ACT (African Conservation Tillage), and the private sector, international organizations and donors.

Reported average of values of carbon sequestration by CA in agricultural soils found in literature for each climatic zone in Africa are presented in Table 1. The total carbon sequestration estimated for the whole of Africa, of 1,543,022 Mg C yr^{-1} is shown in Table 2. On average, the carbon sequestered for Africa due to CA is thus around 1 Mg C ha^{-1} yr^{-1}, corresponding to a total amount of 5,657,747 Mg CO_2 yr^{-1}. This relatively high figure is because degraded soils are 'hungry' for carbon, as the degradation caused by years of tillage, soil mining and crop biomass removal has resulted in a drastic reduction of soil's organic matter (Reicosky, 1995; Jat et al., 2014; Kassam et al., 2017b).

Results presented in this paper are in agreement with previous meta-analyses and studies, where CA in annual and perennial crops have been found to have incremented soil organic carbon (González-Sánchez et al., 2012, 2017; and the studies referenced for obtaining the C sequestration rates for Africa).

In CA systems major inputs in carbon can be expected through the retention of crop biomass, crop rotation and the reduction in soil disturbance (Cheesman et al., 2016). Conversely to the results presented for Africa in this article, González-Sánchez et al. (2012) in a study for European agriculture found that C sequestration rates for perennials were higher than for annual crops. This might be because African perennial crops are not as intensive as yet as European ones, and therefore their soils are closer to the carbon sequestration plateau or the equilibrium.

Sometimes, controversial results can be found in literature attributed to CA when in fact some of the key CA principles were not applied, thus not dealing with real CA systems. Indeed, according to Derpsch et al. (2014), broad understanding is lacking of what CA systems research means. This has led to a situation of conflicting research results because different technologies, methodologies, and erroneous definitions of CA systems have been applied. A practice such as no-tillage can only be considered to be a CA practice if it is part of a CA system as per the definition provided earlier, otherwise it is just a no-tillage practice. Similarly, for soil mulch practice and crop diversification practice both of which can only be considered to be CA practices if they are part of a CA system based on the application of the three interlinked principles. Only when the three principles of CA are applied in field, the best results are achieved, including for carbon sequestration, as confirmed in a recent study for Africa by Corbeels et al. (2018).

These positive results from CA systems are compared with the "business as usual" tillage agriculture cases. Conventional farming globally is based on soil tillage which promotes the mineralization of soil organic matter whilst increasing the release of CO_2 into the atmosphere due to C oxidation. Also, tillage operations can incorporate crop

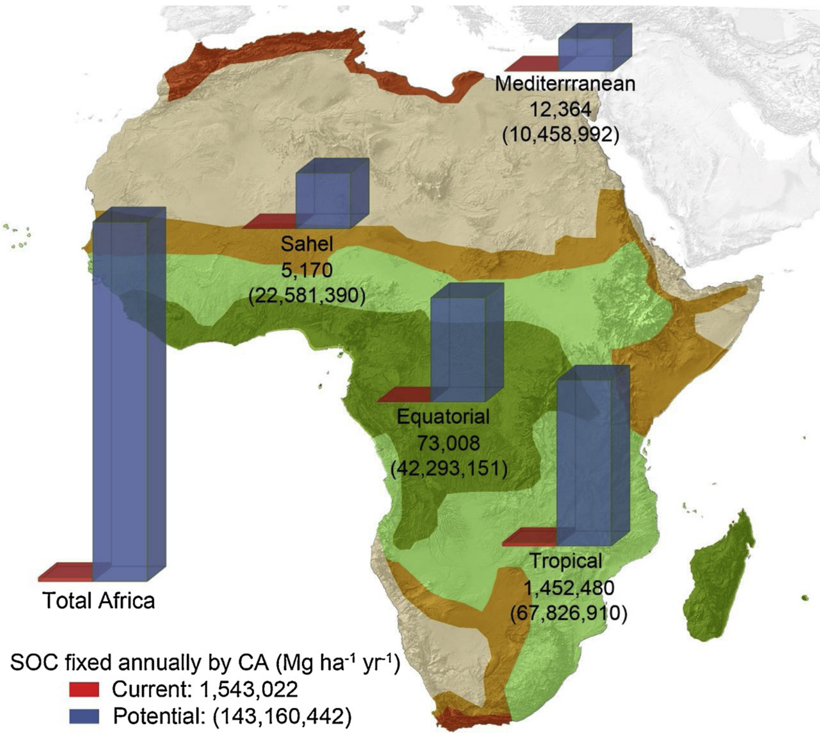

Fig. 5. Potential soil organic carbon (SOC) fixed annually by CA cropland systems compared to tillage-based agricultural production systems in Africa. Authors diagram.

biomass into soil layers where microorganisms and moisture conditions favour their decomposition and thus resulting in more carbon oxidation. Moreover, soil tillage physically breaks down soil aggregates and leaves carbon in them exposed to the action of soil microorganisms which were encapsulated and thus protected within the soil aggregates that existed prior to the performance of tillage (Reicosky and Archer, 2007).

One of the consequences of management systems based on tillage is the reduction of the soil carbon sink effect, which has as a consequence the decrease in the content of organic carbon. This decrease is the result of (1) the lower contribution of organic matter in the form of crop stubble and biomass from previous crops; and (2) the higher rate of mineralization of soil humus caused by tillage. Tillage facilitates the penetration of air into the soil and therefore the decomposition and mineralization of humus, a process that includes a series of oxidation reactions, generating CO_2 as the main byproduct. One part of CO_2 becomes trapped in the porous space of the soil, while the other part is released into the atmosphere through diffusion across the zones of the soil with different concentration; and (3) the higher rate of soil erosion and degradation which causes significant losses of organic matter and minerals as well as soil health. In conventional tillage agriculture, the preparation of soil for sowing and crop establishment leaves the soil exposed to erosive agents for longer periods of time. For all of the above reasons, many researchers agree that mechanical soil disturbance by tillage is one of the main causes of organic carbon reduction in the soil (Balesdent et al., 1990; Six et al., 2004; Olson et al., 2005). Reicosky (2011) argues that intensive tillage agriculture has contributed to the loss of between 30% and 50% of soil organic C in the last two decades of the 20th century. Kinsella (1995) estimates that, in only 10 years of tillage, some 30% of the original soil organic matter was lost.

Even though CA has positive effects, the increase of soil C is not permanent in time, and after a number of years, the rate of accumulation slows down towards a plateau level depending on the soil type, length of growing period and climatic conditions, and the rate of turnover of C. The time to reach the plateau level varies but is considerable, and may take over 10–15 years before a deceleration in the rate of C increase is observed (González-Sánchez et al., 2012). Therefore, even if after 10–15 years C sequestration rates are lower, carbon is still being captured in the soil which supports the value of a long-term and continuing engagement with CA land management. Also, even when top soil layers may be reaching plateau levels, deeper soil layers continue to sequester C through the action of earthworms and biomass and carbon exudates provided by deeper root systems. As CA adoption rates in Africa are improving more significantly over the last decade, the sequestration coefficients presented in this paper can be considered as those applicable to the initial period of transformation from conventional agriculture.

In Figs. 3 and 4, the potential area that could be shifted from conventional tillage agriculture to CA is presented, for both annual and permanent cropping systems. Multiplying the rates of C sequestration presented in Table 1 by the potential areas per country and per type of crop (Tables 3 and 4) permits estimates of the potential carbon sequestration following the application of CA in the agricultural lands of Africa. Where more than one climate affects a single country, the climate of the major cropping area has been selected, i.e. Algeria's rate of C sequestration has been that of the Mediterranean climate, as most of its cropland is affected by that climate. In cases where there were two co-dominant climates, two rates of C sequestration have been applied.

Finally, Fig. 5 shows the total amount of potential carbon sequestration for Africa, for each climatic region, with respect to current carbon sequestration status. Table 5 offers the same result as Fig 5, but split by country. In total, the potential estimate of annual carbon sequestration in African agricultural soils through CA amounts to 143 Tg of C per year, that is 524 Tg of CO_2 per year. This figure represents about 93 times the current sequestration figure. To put this figure into context, according to the United Nations Framework Convention on Climate Change, South Africa, the world's 13th largest CO_2 emitter, total national emissions by 2025 and 2030 will be in a range between 398 and 614 Tg CO_2–eq per year (UNFCCC, 2018). Thus, the carbon dioxide sequestration potential of CA for Africa is almost 3 time higher than that document for Europe by González-Sánchez et al. (2017), i.e. 189 Tg CO_2 per year.

Table 5
Potential annual carbon sequestration in Conservation Agriculture over conventional tillage-based agriculture (annual plus woody crops).

Country	Potential annual carbon sequestration in Conservation Agriculture (Mg yr^{-1})	Climatic zone
Algeria	2,060,377	Mediterranean
Angola	2,029,809	Equatorial
	1,351,855	Tropical
Benin	2,955,789	Equatorial
Botswana	60,234	Sahel
Burkina Faso	6,548,604	Tropical
Burundi	468,425	Tropical
Cabo Verde	65,014	Tropical
Cameroon	2,559,016	Equatorial
	1,710,779	Tropical
Central African Republic	529,915	Equatorial
Chad	1,026,825	Sahel
	2,097,075	Tropical
Comoros	23,591	Tropical
Congo	82,080	Equatorial
Côte d'Ivoire	2,753,996	Equatorial
Democratic Republic of the Congo	3,829,127	Equatorial
Equatorial Guinea	3,013	Equatorial
Eritrea	299,234	Sahel
Ethiopia	1,540,525	Sahel
	9,758,029	Tropical
Gabon	63,468	Equatorial
Gambia	220,614	Tropical
Ghana	3,018,121	Equatorial
Guinea	1,079,185	Equatorial
	764,283	Tropical
Guinea-Bissau	499,907	Tropical
Kenya	1,166,276	Sahel
	2,451,736	Tropical
Lesotho	90,849	Tropical
Liberia	15,206	Equatorial
Libya	800,339	Mediterranean
Madagascar	623,924	Equatorial
Malawi	2,934,478	Tropical
Mali	1,449,675	Sahel
	3,009,681	Tropical
Mauritania	171,118	Sahel
Mauritius	669	Equatorial
Morocco	4,007,541	Mediterranean
Mozambique	3,271,157	Tropical
Namibia	152,674	Sahel
Niger	8,186,196	Sahel
Nigeria	16,700,388	Equatorial
	11,470,375	Tropical
Reunion	8,082	Equatorial
Rwanda	815,998	Equatorial
	548,614	Tropical
Sao Tome and Principe	1,592	Equatorial
Senegal	365,953	Sahel
	764,000	Tropical
Seychelles	64	Tropical
Sierra Leone	405,433	Equatorial
Somalia	218,064	Sahel
South Africa	317,988	Mediterranean
	299,172	Sahel
	1,906,494	Tropical
South Sudan	1,256,381	Tropical
Sudan	7,645,446	Sahel
Swaziland	98,651	Tropical
Tanzania	10,886,052	Tropical
Togo	2,391,500	Equatorial
Tunisia	3,272,747	Mediterranean
Uganda	2,426,840	Equatorial
	1,705,664	Tropical
Zambia	1,687,985	Tropical
Zimbabwe	2,236,555	Tropical
TOTAL	**143,160,442**	

4. Conclusions

Conservation Agriculture is a promising sustainable agricultural system, as it can effectively contribute to mitigating global warming, being able to sequester carbon in the soil, thus offsetting agricultural and non-agricultural CO_2 emissions. CA is a proven and effective agricultural system that African countries need to promote to fulfill the international agreements and initiatives related to climate change mitigation and adaptation, such as the Paris agreement on climate change, the 4p1000 initiative and the Adaptation of African Agriculture (AAA).

Carbon sequestration rates in Africa are in agreement with those found in other meta-analyses performed in other agroclimatic regions. As performed in this review, the accounting methodology for carbon sequestration in agricultural soils should be based on the relative gains when compared to conventional tillage-based agriculture. In addition, and with regard to African carbon sinks, areas of annual and perennial cropping systems when converted to CA should be accounted for as new net carbon gains, both in the carbon markets and the international climate change agreements.

According to the estimation of the climate change mitigation capacity through CA in Africa there exists an enormous C sink potential which is around 93 times greater than under the current situation, i.e. at present only around 1.1% of the overall C sequestration potential through CA is used.

Acknowledgements

The authors would like to thank the LIFE financial instrument of the European Union for co-financing the LIFE + ClimAgri project “Best agricultural practices for Climate Change: Integrating strategies for mitigation and adaptation - LIFE13 ENV/ES/000541”, the LIFE AGROMITIGA project “Development of climate change mitigation strategies through carbon-smart agriculture - LIFE17 CCM/ES/000140” and the support of the Plan Propio de Fomento de la Investigación (Internal University Research Plan) (2018) of the Universidad de Córdoba that allowed the first author visiting the Imperial College London.

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